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FREQUENCY OF MAXIMUM WIND SPEEDS

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FREQUENCY OF MAXIMUM WIND SPEEDS[1]

H. C. S. Thom[2]

ABSTRACT

The design wind speed for determining critical stresses in structures is a probability statistic on a suitable function of the wind speed observations. Analysis of wind speed observations and functions of them suggests that the annual extremes of the fastest mile observations of the Weather Bureau provide the best available series for determining design wind speeds. A formula for reduction of these series to standard and arbitrary heights above ground is given. A method of fitting the Fisher-Tippett Type II distribution to standardized series is developed and applied to the series for Fort Wayne. A probability paper for this distribution is also developed and applied in the fitting of the distribution.

INTRODUCTION

Engineers have long used extreme values of wind speed in various forms to determine design wind pressures and loads. These wind speeds were often defined simply as the highest speed ever recorded at a particular station. It was soon noted that the value of this extreme depended on the length of record which varies considerably from station to station making the design winds a function of other factors than climatic experience. Even with equal lengths of records at all stations the sampling variability of the single extreme value is so large that it furnishes only a vague indication of what the design wind should be. An even more serious weakness of the single extreme may be its indefiniteness in respect of the risk of winds exceeding it. The solution to these difficulties seemed to lie mainly in a clearer definition of the climatological problem of providing wind statistics suitable for use by the engineer in determining design wind speeds. Only the climatological aspects of this problem will be treated here, the actual choice of design wind value being left to the engineer.

The Design Wind Speed Variable

It is well recognized that high wind speeds cannot be fully predicted from physical analysis alone, for wind speed is a statistical variable subject to the usual random fluctuations of such variables. The solution to the design wind problem must therefore come from a statistical

1. Prepared in cooperation with the Naval Aerology Branch.
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analysis of climatological series of wind data. More specifically the problem resolves itself into three parts: (1) the choice of wind observation, (2) the choice of the function of this wind observation, and (3) the choice of the type of statistic for determining the design wind.

The first part of the problem is limited to two alternatives, since weather records in the United States only contain two wind observations suitable for measuring the effects of critical wind loading on structures. These are the daily maximum speed for five minutes and the daily extreme mile or the mile of air having the highest speed. The latter comes conveniently from an instrument which tallies each mile of wind passage on a time chart. The extreme mile or fastest mile is then simply the tallied mile covering the shortest distance on the time chart.

It is assumed that dangerous wind loads in structures are more often the result of relatively short bursts of wind rather than longer sustained winds which average to lower speeds. On this basis the extreme mile would be most closely related to the shorter bursts of high speeds for at 60 miles per hour one mile of air would be observed for the extreme mile whereas five miles would be observed for the five minute maximum wind since the observation extends over five times the length of time. The latter of course results in a considerable amount of averaging and hence reduction in wind speed. It is seen also that the length of time of averaging for the two observations is equivalent at 12 miles per hour, for here the fastest or extreme mile takes five minutes to record. Hence it might be argued from the length of averaging time alone that the extreme mile is a superior measurement of the higher wind gusts. On this basis we choose the daily extreme mile observations for further analysis although presumably the main part of our analysis could also be applied to the five minute maximum winds.

Having chosen the observation to be used, consideration must now be given to the function of this observation. It is clear that only a few daily extreme winds can have much effect on structural design. These few winds, therefore, must be given a preponderant weight in contrast to the many unimportant smaller daily extreme winds. Hence the best procedure seems to be to also take the extreme value of some sample of daily extremes. The choice of this second extreme must be made with the requirements of the problem well in mind. For example, the operators of an airport would be much interested in the monthly extreme wind speeds, for they could adjust some operating procedures through the different months of the year according to expected extreme winds. A permanent structure, on the other hand, must withstand critical winds in all months and therefore, also, the extreme wind of the year. If it withstands the annual extreme, it is of little importance that it also withstood the eleven lower monthly extreme winds, the lower extremes being then superfluous for structural design purposes except as they determine the period of risk and the pertinent extreme. The monthly extremes form a mixed statistical population in which the month is randomized and the annual extremes therefore comprise only one-twelfth of this population. Statistics from the mixed population would greatly underestimate the critical importance of the annual extreme and result in much too low design values. It is clear that all periods less than a year have a similar weakness and therefore the year is the minimum period for the extreme

function. Series of extremes for multiples of a year clearly result in a waste of data and further do not reflect the natural annual recurrence of weather conditions. The year therefore is the proper period for the extreme function.

In cases where the design factor forms a statistical population, as it does for annual extreme winds, it is more and more being recognized by engineers that a quantile is the correct design value. The quantile is a critical value which will be exceeded with a certain probability or with a corresponding recurrence interval or return period. It is determined by choosing a probability or risk on the basis of engineering analysis and obtaining the corresponding design value from the frequency curve of the design variable. The analysis presented here will be limited to providing a frequency distribution from which any quantile can be obtained.

Standard Level Conversion

The wind instruments at the various stations of the U. S. Weather Bureau have by necessity been moved occasionally through the period of their operation. These moves have resulted in changes in elevation above ground which have in turn affected the speed regime. Since some of these elevation changes have been rather large, it is necessary to convert wind speeds to a standard level to obtain a homogeneous statistical series. The standard level chosen for this study was 30 feet as this level appeared to be satisfactory for many engineering uses. The choice is arbitrary and not restrictive, for quantiles may readily be converted to other levels by the same method of conversion.

The standard formula for converting wind speeds from level to level is the power law

$$V_z = V_o \left(\frac{z}{z_o}\right)^{\frac{1}{n}} \qquad (1)$$

where V_o is the speed at the height above ground z_o, V_z is the speed at the height z, and n is a constant. Huss[1] has studied the application of this relationship to extreme mile wind speeds taken at various levels and has found an average value for n of about 7. This is in accord with previous experimental evidence which gave rise to the well-known seventh root law commonly used for speed-height conversions. Using n = 7, z = 30, and taking logarithms we have

$$\log V_z = \log V_o + \tfrac{1}{7}\left(\log 30 - \log z_o\right). \qquad (2)$$

This relationship was used to homogenize the extreme wind data series studied here.

The Distribution of Extreme Wind Speed

Each annual extreme speed (fastest mile) is the highest of 365 daily extreme speeds and is also, of course, the highest of all possible of a

large number of mile-of-wind observations which could be made through a year. These possible observations would comprise a population and hence a frequency distribution with a zero lower bound since wind speed cannot be negative. The series of annual extremes from this population then form a distribution called an extreme value distribution which is evidently the distribution of interest in this study. The general properties of this class of distributions has been extensively studied by mathematical statisticians (see references 2 to 4). Fisher and Tippett[2] more particularly have given the integrated theory for all possible limiting extreme value distributions, von Mises[4] and Norton[5] have generalized their results. It is this distribution theory which is applied here.

Fisher and Tippett[2] found that irrespective of the distribution of the original data the limiting extreme value distribution can only take three forms. For convenience these will be called Type I, II, and III. The Fisher-Tippett Type I distribution is the one extensively employed by Gumbel[3] and is the limiting form of Types II and III. If F(x) is the probability of a value being less than x the three distributions are as follows:

$$\text{I. } F(x) = e^{-e^{-x}}$$

$$\text{II. } F(x) = e^{-x^{-\gamma}} \qquad (3)$$

$$\text{III. } F(x) = e^{-(-x)^{\gamma}}$$

Types II and III are only different in the sign of x and γ; so if $\gamma = 1/\delta$, II and III approach I as δ approaches zero. This completes the system of distributions with δ as a parameter, for $\delta < 0$ is Type II, $\delta > 0$ is Type III, and $\delta \to 0$ is Type I. The latter results are due to von Mises[4] and Norton[5].

It is noted that Types II and III are bounded at zero, below and above respectively, while Type I is unbounded at both ends. x is a normalized variable, and more generally x will be measured from some location α and will be scaled in units β. Thus x may be expressed as $(x - \alpha)/\beta$ where α is any number and $\beta > 0$. Wind has a strict physical lower bound of zero but no known physical least upper bound, so for any observed high wind there is a probability of it being exceeded. It seemed logical therefore to choose Type II for fitting extreme winds since like wind, it has a natural lower bound and an upper bound defined only by the smallness of a probability. For this range of x the Type II distribution equation (3) becomes a two parameter distribution

$$F(x) = e^{-\left(\frac{x}{\beta}\right)^{-\gamma}} \qquad x > 0, \ \beta > 0. \qquad (4)$$

It is easily seen that when $x = \beta$, $F(x) = e^{-1} = .368$, hence all the curves for a given β pass through a common point. This is illustrated in Figure 1 which shows curves for $\beta = 35$ and various values of γ.

The rapidity with which the probability F(x) approaches zero for x with probability less than 0.1 gives the impression of a lower bound greater than x = 0. Actually the curves have a zero bound and are simply exhibiting the property that the probability of an extreme value being near the lower bound of the original population must be extremely small.

Probability Paper

Although probability papers are occasionally misused, they are convenient for depicting probability distributions and for obtaining preliminary estimates of the distribution parameters. All distributions do not lend themselves readily to the preparation of probability papers, however, the distribution, equation (3), is easily put in the form for compilation of probability paper. Taking the double logarithm of the reciprocal of equation (3) gives

$$\log \log \left[1/F(x)\right] = \gamma \left(\log x - \log \beta\right). \tag{5}$$

Here a function of F(x) is an explicit linear function of log x. Hence if the scale of F(x) is transformed into log log[1/ F(x)] and labeled in F(x), the distributions of this form will be straight lines in the variable log x. If a plotting paper is made with log log [1/F(x)] on the ordinate and log x on the abscissa, all F(x) will plot as straight lines with slope γ and intercept $\gamma \log \beta$. As mentioned previously when $x = \beta$, $F(x) = e^{-1} = 0.368$, so that the x intercept of the probability line at F(x) = 0.368 is the value of β. Values of γ may be obtained from the equation by solving (5) for γ giving

$$\gamma = \frac{\log \log \left[1/F(x)\right]}{\log \beta - \log x}. \tag{6}$$

This defines the slope of the probability distribution on the plotting paper. Figure 3 is a sheet of this paper constructed on these principles.

The probability scale on the left of Figure 3 may be converted to a recurrence interval or return period scale by means of the relationship

$$R = 1 / \left[1 - F(x)\right]. \tag{7}$$

Here R is the recurrence interval and gives the mean interval of recurrence or return period of values exceeding the corresponding x value. The R-scale is shown on the right of Figure 3.

The plotting position of the data points on probability graphs has been the subject of much discussion in the past. Gumbel[6] has developed asymptotic plotting positions for extreme values from a normal distribution. These probability plotting positions are closely approximated by m/(n + 1) where m is the serial number of the m^{th} value for the sample series of length n arranged by increasing order of magnitude. Hence the empirical probabilities are

$$F(x) = m/(n+1). \tag{8}$$

Figure 3 shows the data for Fort Wayne plotted according to this procedure.

Fitting the Extreme Value Distribution

While the parameters β and γ and hence F(x) could be estimated from the plotting paper, this is an inefficient procedure which has been shown to use only a part of the information about F(x) available in the sample. In some instances the portion of the information used is a small percentage of the total available and so estimation using the paper is poor. In addition to the graphical procedure there are many analytical methods of estimation among which are the method of least squares which is well known to engineers. Least squares, however, also has its deficiencies and in any case is at most as good as the method of maximal liklihood[7], the estimating procedure most commonly used by statisticians.

While the method of least squares minimizes the residuals of the data about the fitted function to give the estimates of the parameters, the method of maximal liklihood (M.L.) maximizes the liklihood that the estimated parameter values should have come from the sample at hand. If $f(x) = F'(x)$, the derivative of F(x), then the M. L. estimates are derived by maximizing the product

$$\prod_{i=1}^{n} f(x_i, \beta, \gamma). \tag{9}$$

in respect to β and γ where the x_i are the n sample values and β and γ are as previously. The maximizing process may most easily be accomplished by operating with the logarithm. Taking logarithms, (9) gives

$$L = \sum_{i=1}^{n} \log f(x_i, \beta, \gamma). \tag{10}$$

The conditions for maximum L in respect to β and γ are

$$\frac{\partial L}{\partial \hat{\beta}} = 0 \text{ and } \frac{\partial L}{\partial \hat{\gamma}} = 0. \tag{11}$$

The simultaneous solution of these differential equations gives the M. L. estimates $\hat{\beta}$ and $\hat{\gamma}$. This procedure furnishes the best possible estimates of β and γ, for it extracts the largest proportion of available information on these parameters from the sample.

Maximizing the liklihood function of the Type II distribution equation (3) gives

$$\frac{\partial L}{\partial \hat{\beta}} = \frac{n}{\beta} - \hat{\beta}^{\hat{\gamma}-1} \sum_{i=1}^{n} x_i^{-\hat{\gamma}} = 0 \tag{12}$$

$$\frac{\partial L}{\partial \hat{\gamma}} = \frac{n}{\hat{\gamma}} - \sum_{i=1}^{n} \log x_i + \frac{n \sum_{i=1}^{n} x_i^{-\hat{\gamma}} \log x_i}{\sum_{i=1}^{n} x_i^{-\hat{\gamma}}} = 0 \qquad (13)$$

It is clear that equations (11) and (12) are not easily solved. (13) is independent of $\hat{\beta}$ but is not explicit in $\hat{\gamma}$ and hence must be solved by some successive approximation procedure. Expressing (13) as

$$\lambda(\gamma) = 0 \qquad (14)$$

the problem is to find the value of γ which satisfies (14). It is seen that each value of γ together with the sample values (x_i) give rise to a value $\lambda(\gamma)$. Using the data for Fort Wayne $\lambda(\gamma)$ is plotted as a function of γ in Figure 2. From here $\hat{\gamma}$, the solution of (13), is found at the intersection of the curve with the γ-axis.

λ is more easily computed for integral values of γ but still difficult; so that the fewer values which need to be computed the better. The number of values needed may be minimized by obtaining a preliminary estimate of $\hat{\gamma}$ from the empirical slope of the probability distribution on the probability paper using equation (6). This will locate $\hat{\gamma}$ between two integral values which, when computed together with one or two other values will allow a good approximation to λ around zero. Drawing the curve through these points immediately gives $\hat{\gamma}$, the solution of $\lambda(\gamma) = 0$.

In Figure 2 this procedure has been carried out for Fort Wayne, Indiana. A preliminary estimate of γ, 6.8, found from a line of rough approximation to the plotted points in Figure 3 (not the line shown), brackets the exact value of $\hat{\gamma}$ between 6 and 7. Since it is nearer 7, the values of λ for $\gamma = 6$, 7, and 8 were computed and plotted in Figure 2. After drawing the curve the exact value of $\hat{\gamma}$, 6.96, was read at $\lambda = 0$. This value was then substituted in equation (12) to obtain $\hat{\beta} = 36.60$. Using the two values the curve of best fit was drawn as shown in Figure 3.

The preliminary graphical estimate may be eliminated by using an iteration process for finding $\lambda(\gamma) = 0$. Such an iteration cannot be carried out manually without great difficulty but can, of course, be done readily on an electronic computer or some of the more powerful IBM computers. A completely numerical iterated solution has been developed for the IBM Card Program Calculator, which fits a curve in 10 minutes as compared to three hours required for manual estimation.

Figure 3 may now be used to determine any quantile for design purposes. For example, suppose the risk is 0.01 or a 100 year recurrence interval. The quantile 71 miles/hour at 30 feet above ground is read at F(.99) or R = 100. The chart makes design speeds readily available for any risk the engineer wishes to take.

ACKNOWLEDGMENT

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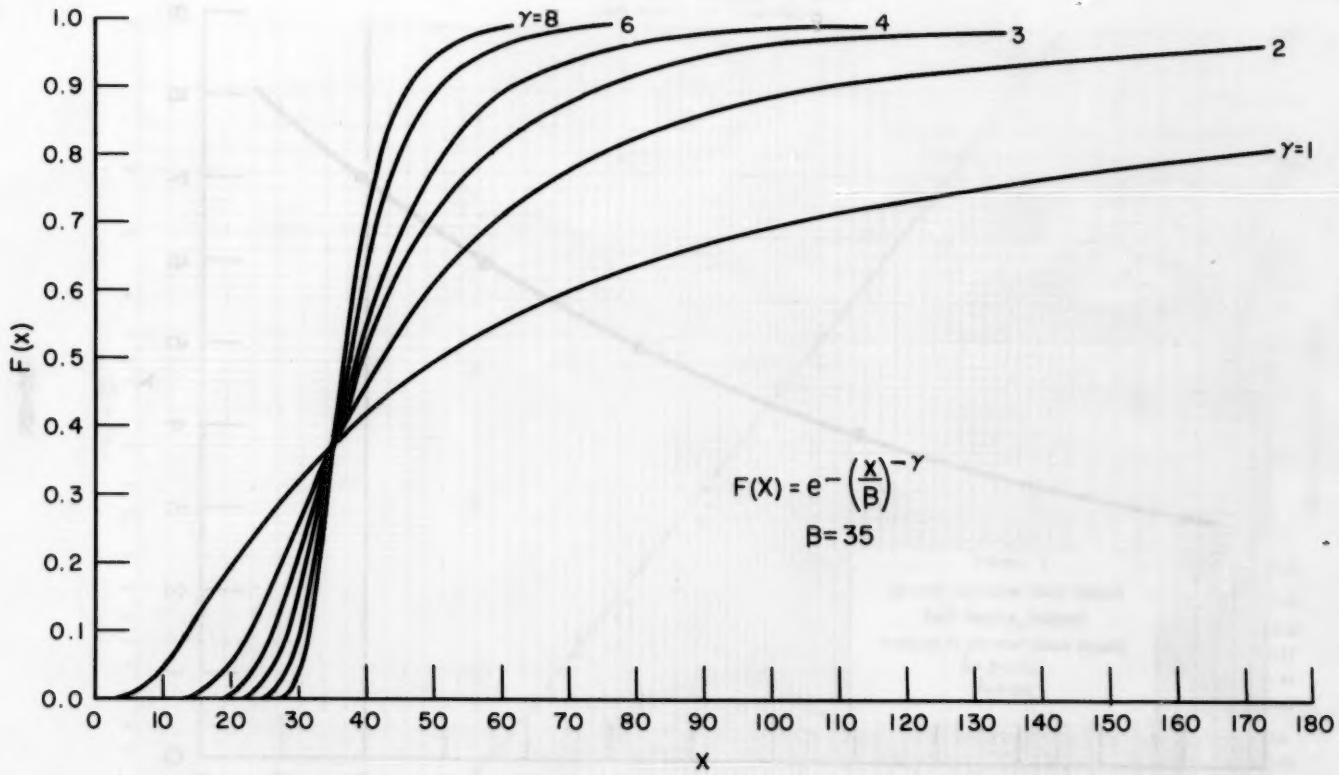

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Figure 1.—Graphs of F(x) for various γ's.

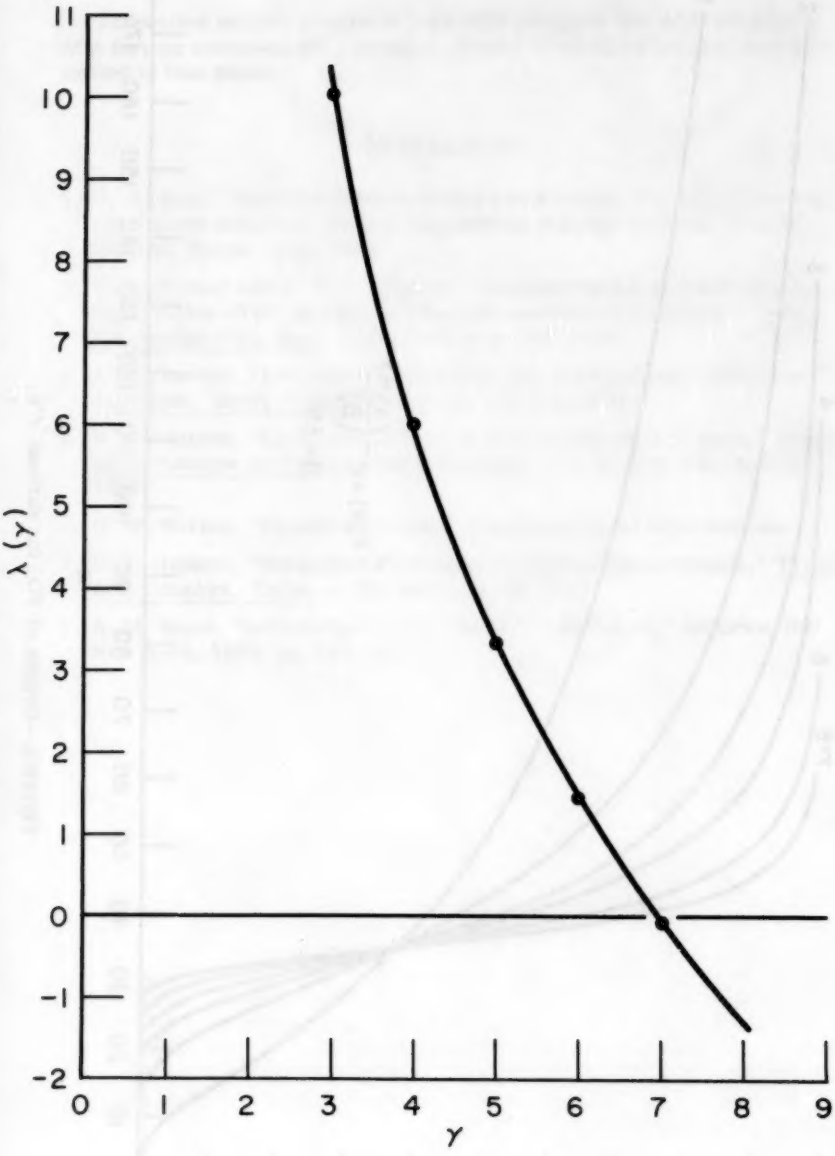
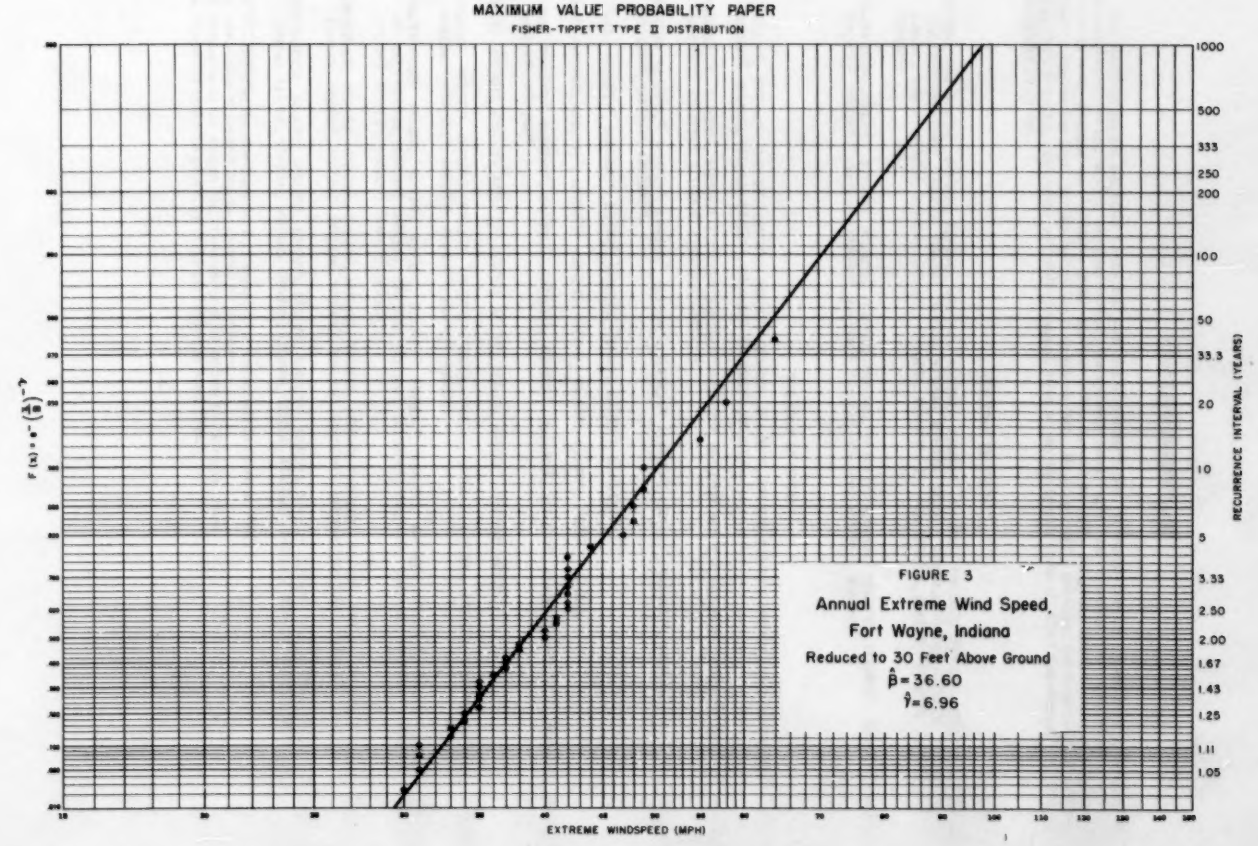


Figure 2.—Graph of approximation of $\hat{\gamma}$.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$F(x) = e^{-\left(\frac{\beta}{x}\right)^{\gamma}}$
1000
500
333
250
200
100
50
33.3
20
10
5
3.33
2.50
2.00
1.67
1.43
1.25
1.11
1.05
RECURRENCE INTERVAL (YEARS)
EXTREME WINDSPEED (MPH)
FIGURE 3
Annual Extreme Wind Speed,
Fort Wayne, Indiana
Reduced to 30 Feet Above Ground
$\hat{\beta} = 36.60$
$\hat{\gamma} = 6.96$

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a. Presented at the New York (N.Y.) Convention of the Society in October, 1953.
c. Discussion of several papers, grouped by Divisions.
d. Presented at the Atlanta (Ga.) Convention of the Society in February, 1954.
e. Presented at the Atlantic City (N.J.) Convention in June, 1954.

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